CFD analysis of flow patterns and resistance of air filter media having random fiber diameters

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AFS

American Filtration & Separations Society

Educating and Networking Industry Professionals

www.afssociety.org

WELCOME ATTENDEES

On behalf of the American Filtration and Separations Society and the dedicated Conference Program Committee, it is our honor to welcome you to the 19th Annual AFS Conference and Exposition, co-hosted under the generous umbrella of the Powder and Bulk Solids (PBS) event at the Donald E. Stephens Convention Center in Rosemont, IL. The volunteers of the 2006 Program Committee have worked to assemble an expansive technical program set against a rich backdrop of spectacular exhibits.

As many of you know, the AFS is expanding our educational offerings. In fact, three new programs have been added this year. Our goal is to be the world's leading industrial and instructional society in the field of Filtration and Separations Technology. As Chair of the 2006 Program Committee, I applaud the efforts of the volunteers that spent many hours recruiting and assembling presentations for the conference. Presented here is our 2006 Program team:

- Mr. Chris Shields, Product and Technical Manager, Finetex Technology, Inc.
  Solid/Liquid Filtration and Separations Technology Sessions
- Dr. Barry Verdegan, Research Fellow, Fleetguard, Inc.
  Air and Gas Filtration and Separations Technology Sessions
- Dr. Heidi Schreuder-Gibson, Research Chemist, US Army Natick Soldier Center
  Student Technical Poster Sessions
- Dr. Wu Chen, Senior Solids/Liquids Separations Specialist, Dow Chemical
  Short Course Coordinator and Chairman of the Education, Committee for the AFS
- Ms. Faith Levine, Marketing Manager, American Filtration and Separations Society
  AFS Filtration and Separations Technology Exhibits
- Ms. Suzanne Sower, Administrative Manager, American Filtration and Separations Society
  Suzanne and Ken Sower are the glue that holds our society together

We would also like to thank Mr. Scott Temple, Cindy Strachan, Molly Lanute, Matt Luke, Allison Alessio and Mike Feighery from Reed Exhibitions for their efforts in coordinating and supporting the AFS in facilitating the details of this event. They have served the AFS tirelessly. I would like you all to know that both Reed Exhibitions and the AFS have an eye toward 2008 and are working to develop this into the most complete Industrial Filtration and Separations Technology Pavilion in the USA.

As we move forward, the AFS Long Range Plan has targeted expansion of our education programs as a top priority. With that goal in mind, it is our hope that the Society has served your educational and professional development needs, while providing you with invaluable networking opportunities.

THANK YOU FOR YOUR PARTICIPATION AND SUPPORT OF THE 2006 ANNUAL EVENT.

Best Regards,

Gerard J Lynch

Gerard (Jerry) Lynch
Chairman, Program Committee
American Filtration & Separations Society

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SCHEDULE OF EVENTS

MONDAY, MAY 8, 2006

07:30 – 17:00	**REGISTRATION**
08:00 – 17:00	Short Courses

TUESDAY, MAY 9, 2006

07:00	**PRE-REGISTERED REGITRATION OPENS**
07:15–8:15	Speakers Breakfast
07:30–17:00	**REGISTRATION**
08:20–9:50	Plenary Session
10:00	Exhibition Opens
10:00–10:20	**BREAK**
10:20–12:00	Concurrent Technical Sessions
12:00–13:20	**AWARDS LUNCH**
13:20–15:00	Concurrent Technical Sessions
15:00–15:20	**BREAK**
15:20–16:35	Concurrent Technical Sessions
16:00	Exhibition Closes
16:35	Student Poster Session
17:00–18:30	Networking Reception

WEDNESDAY, MAY 10, 2006

07:00	**PRE-REGISTERED REGISTRATION OPENS**
07:15–8:15	Speakers Breakfast
07:15–8:15	Corporate Sponsors Breakfast
07:30–17:00	**REGISTRATION**
08:20–10:00	Concurrent Technical Sessions
10:00	Exhibition Opens
10:00–10:30	**BREAK**
10:30–12:00	Keynote Speaker
12:00–13:00	**COMBINED LUNCH WITH PBS**
13:20–15:00	Concurrent Technical Sessions
15:00–15:20	**BREAK**
15:20–17:00	Concurrent Technical Sessions
16:00	Exhibition Closes
17:00	Board Meeting

THURSDAY, MAY 11, 2006

07:00	**PRE-REGISTERED REGISTRATION OPENS**
07:15–8:15	Speakers Breakfast
07:30–12:00	**REGISTRATION**
08:20–10:00	Concurrent Technical Sessions
10:00	Exhibition Opens
10:00–10:20	**BREAK**
10:20–12:00	Concurrent Technical Sessions
15:00	Exhibition Closes

SPEAKERS BREAKFAST

Tuesday, Wednesday, Thursday, 07:15-08:15

ROOM 59

There will be a breakfast each morning of the Conference for speakers and presenters of the day. Information concerning the technical session schedules and operations will be presented at this breakfast. Session Moderators and members of the Program Committee will be on hand to confirm details for each session. All Session Moderators and Speakers should attend the Speakers' Breakfast for their scheduled date.

LOCATIONS

SHORT COURSES

Monday, May 8

Liquid Filtration Basic Course – Rms 50-51
Gas Filtration Basic Course – Rms 52-53
Microfiltration Membrane Course – Rms 55-57

TECHNICAL SESSION ROOMS

Tuesday, May 9 – Thursday, May 11

Track 1 – Rms 50-51
Track 2 – Rms 52-53
Track 3 – Rms 55-57
Track 4 – Rms 54-56-58

OTHER FUNCTIONS

SPEAKER'S BREAKFASTS
Tuesday, May 9 – Thursday, May 11
Rm 59

PLENARY SESSION
Tuesday, May 9
Rm 46-48

AWARDS LUNCH
Tuesday, May 9
Rm 46-48

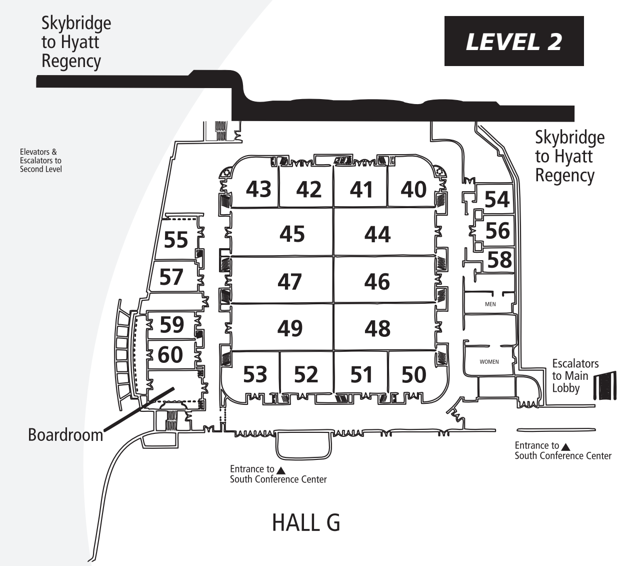
CORPORATE SPONSOR'S BREAKFAST
Wednesday, May 10
Rm 60

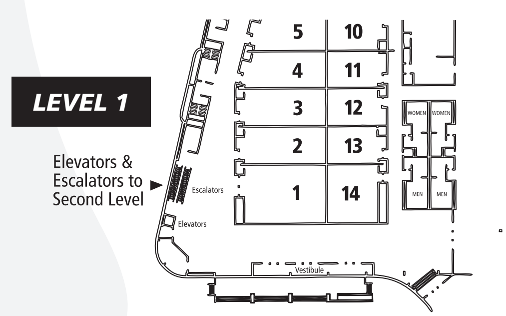
KEYNOTE ADDRESS
Wednesday, May 10
Rm 1

WEDNESDAY LUNCH
Wednesday, May 10
Rms 2-3

AFS BOARD OF DIRECTORS MEETING
Wednesday, May 10
Rm 40

NETWORKING RECEPTION
Tuesday, May 9
Rm 44





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Booth#	Company
3917	BHS - Filtration
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PLENARY SESSION

Tuesday, May 9, 2006
ROOM 59

Speaker— Dr. Dean Tompkins

Dr. Tompkins received his PhD in Mechanical Engineering from the University of Wisconsin – Madison, specializing in thermal fluid systems and heating, ventilating, and air conditioning. Since 1995 he has been Scientist in the Environmental Chemistry and Technology Program at the University of Wisconsin. In that position he studies metal oxides that form suspensions of nanoparticles such as titania, silica, alumina, among others. These nanoparticles are utilized as catalysts, photocatalysts and thin-film batteries and find application in green technologies associated with clean water, clean air and clean power generation such as fuel cells. He has studied these materials from their fundamental principals to applications that are currently marketed by industry. Dr. Tompkins is co-founder of two spin-off businesses from technology developed at the UW-Madison. He is currently Vice-Chair of Technical Committee 2.3 (Gaseous Air Contaminants and Removal Systems) of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers or ASHRAE.

Speaker— Dr. Karsten Keller:

Dr. Karsten Keller is recognized as a world expert in solid/liquid separation technology. He joined DuPont in April 1998, and with his vision and skills he positioned to help DuPont attain a strategic position in the emerging bio- and nano-technology based applications and products, which will all require innovative separation technology. He is now a research manager at the DuPont Engineering Research and Technology group.

Dr. Keller's qualifications and credentials prior to his employment at DuPont are outstanding. He studied and obtained his doctoral degree at the European leading Chemical Engineering University of Karlsruhe, Germany. His original contributions in the field of particle technology through patents (8) and publications (over 70) made him well known to the international academic field. In addition, he shows practical success in improvement of processes in varies companies before he joined DuPont.

Dr. Karsten Keller received various internal DuPont awards, while in 2005 he was rewarded with the Frank Tiller Award of the AFS in Recognizing Leadership in Engineering and Education.

Speaker/Presenting for Dr. Keller— Dr. Benjamin Fuchs:

Dr. Benjamin Fuchs also studied and obtained his doctoral degree at the University of Karlsruhe in Germany under the tutelage of Prof. Dr.-Ing. Werner Stahl. From the beginning of is professional career in the field of separations 5 years ago he is a very active contributor to the American Filtration and Separations Society. Besides contributions to the AFS Dr. Fuchs is inventor on 5 patents and (co-) authored more than 20 publications discussing various aspects of solid-liquid separation.

While still finishing his Ph.D. work at the University of Karlsruhe Dr. Fuchs joined DuPont as a research engineer in the particle processing group within the engineering organization end of 2004. In his role Dr. Fuchs assumes research and development accountability in the area of solid-liquid separation. These responsibilities include 60+ solid-liquid separation related projects in support of DuPont's chemical and bioprocessing activities. While moving from academia to industry Dr. Fuchs kept the close ties to the American Filtration and Separations society.

PBS KEYNOTE ADDRESS

Wednesday, May 10; 10:30-12:00
ROOM 1

FROM WORST TO FIRST,
Gordon Bethune, ***Former CEO and Chairman of Continental Airlines***

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thank you thank you thank you thank you thank you thank you thank you thank you thank you

CORPORATE SPONSORS BREAKFAST

Wednesday, 7:15 – Room 60

The Corporate Sponsor Breakfast is an opportunity for corporate sponsors to discuss the vision and programs of AFS.

THANK YOU

A special thank you to the individual Members, Corporate Sponsors, and Distributor/Agency Membership of the AFS who have supported the Society, since it's formation in September 1987. The American Filtration & Separations Society is the largest Filtration Society in the World and principal educator of the industry.

TUESDAY - EXHIBITION OPEN 10:00 - 16:00				
07:15	SPEAKERS BREAKFAST — RM 59			
	LIQUID FILTRATION & SEPARATION SESSIONS		AIR/GAS FILTRATION & SEPARATION SESSIONS	
08:20	AFS PLENARY SESSION — RM 46-48			
10:00	BREAK			
	TRACK 1 — RMS 50–51	TRACK 2 — RMS 52–53	TRACK 3 – RMS 55–57	TRACK 4 — RMS 54–56–58
10:20	BIOPHARMACEUTICAL	APPLICATIONS FOR INDUSTRY I	MOLECULAR FILTRATION - MEDIA AND APPLICATIONS	TESTING HIGH EFFICIENCY FILTER MEDIA & CARTRIDGES
12:00	AWARDS LUNCH — RM 46-48			
13:20	WATER AND WASTEWATER I	APPLICATIONS FOR INDUSTRY II	INNOVATIVE NONWOVEN MEDIA FOR AIR FILTRATION APPS.	INCREASING INDUSTRIAL AIR FILTER SYSTEM PERFORMANCE
15:00	BREAK			
15:20	WATER AND WASTEWATER II	AUTOMOTIVE	AIR FILTER MEDIA	INDUSTRIAL AIR AND GAS FILTRATION
16:30	STUDENT POSTER SESSION: 16:30-18:00 — OUTSIDE ROOM 44			
17:00	END OF SESSIONS • NETWORKING RECEPTION 44			

WEDNESDAY - EXHIBITION OPEN 10:00 - 16:00				
07:15	SPEAKERS BREAKFAST — RM 59			
	LIQUID FILTRATION & SEPARATION SESSIONS		AIR/GAS FILTRATION & SEPARATION SESSIONS	
	TRACK 1 — RMS 50–51	TRACK 2 — RMS 52–53	TRACK 3 – RMS 55–57	TRACK 4 — RMS 54–56–58
08:20	MEMBRANES	NOVEL FILTRATION	AUTOMOTIVE APPLICATIONS	COALESCENCE
10:00	BREAK			
10:30	GORDON BETHUNE – PBS KEYNOTE SPEAKER — RM 1			
12:00	LUNCH — RM 2–3			
13:20	WOVENS/NONWOVENS	THEORY I	ENGINE EMISSIONS	FILTER MEDIA EVALUATION & CHARACTERIZATION
15:00	BREAK			
15:20	NANOTECHNOLOGY	THEORY II	MIST REMOVAL APPLICATIONS	FILTER TESTING
17:00	END OF SESSIONS • BOARD MEETING— RM 40			

THURSDAY - EXHIBITION OPEN OPEN 10:00 - 15:00				
07:15	SPEAKERS BREAKFAST — RM 59			
	LIQUID FILTRATION & SEPARATION SESSIONS		AIR/GAS FILTRATION & SEPARATION SESSIONS	
	TRACK 1 — RMS 50–51	TRACK 2 — RMS 52–53	TRACK 3 – RMS 55–57	TRACK 4 — RMS 54–56–58
08:20	TESTING I	COALESCENCE	FIBROUS FILTER MEDIA CHARACTERIZATION AND MODELING	RECENT DEVELOPMENTS IN HVAC SYSTEMS
10:00	BREAK			
10:20	TESTING II	WQA PLANNING SESSION	MODELING TRANSPORT	NANOPARTICLES AND PERSONAL PROTECTIVE APPLICATIONS
12:00	END OF SESSIONS • 13:30-15:00 BALLPARK RECEPTION • EXHIBITION OPEN UNTIL 15:00			

THE AMERICAN FILTRATION AND SEPARATIONS SOCIETY AND THE TECHNICAL CONFERENCE COMMITTEE PROGRAM FOR THE 2006 ANNUAL CONFERENCES RECOGNIZES THE FOLLOWING SESSION MODERATORS FOR OUR PROGRAM:

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FIBROUS FILTER MEDIA CHARACTERIZATION AND MODELING—M. Lehmann, Dr. Ing., MANN+HUMMEL GMBH, Abt. / Dept.: SE-EFS, Hindenburgstr. 45, 71638 Ludwigsburg, Germany; Phone, ++49 (7141) 98-2271; Fax, ++49 (7141) 98-18 2271; E-mail: martin.lehmann@mann-hummel.com

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NANOPARTICLES AND PERSONAL PROTECTIVE APPLICATIONS—S. Ernest, Ph.D., E-mail, gse0@cdc.gov and H. Schreuder-Gibson, Ph.D., Ph.D., Research Chemist, US Army Natick Soldier Center (NSC), AMSS B-RSS-MS (M) Kansas St., Natick, MA 01760; Phone, 508-233-5487; Fax, 508-233-5521; E-mail, heidi.schreudergibson@us.army.mil

CFD ANALYSIS OF FLOW PATTERNS AND RESISTANCE OF AIR FILTER MEDIA HAVING RANDOM FIBER DIAMETERS

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ABSTRACT

This paper presents a simulation of flow and pressure drop in fibrous media which makes only one basic simplification to the media geometry: that it is modeled with sufficient accuracy by a two-dimensional pattern of circles which are randomly spaced, and whose diameter distribution simulates the fiber diameter distribution. This geometry represents a plane cut through the filter medium perpendicular to the face of the medium, i.e. in the usual direction of the air flow.

The diameters of the circles are distributed in the same way as the diameters of the fibers in the media modeled. The diameter and spacing of the circles, though random, is scaled so that the sum of fiber cross sections divided by the area of the domain is equal to the volume fractional solids in the real media.

This conceptual geometry is converted for CFD purposes into a predominately Cartesian grid with cells near the fiber boundaries being smaller. In the CFD analysis the flow velocity is set uniform and parallel across the domain a short distance upstream of the fibrous medium, and with a uniform gradient a short distance downstream of the fibrous medium. CFD analysis produced streamlined patterns which appeared correct and predicted pressure drops from 120% to 200% of the measured values. However, decreasing the cell's dimensions by steps until the least cell dimension was approximately 5% of the least fiber diameter failed to yield asymptotic stabilization of predicted pressure drops.

Independence of grid scale is essential to valid CFD analysis. The vendor of the CFD code used here has since corrected what appear to have been problems in the solver for the flow equations at the scale required for study of filter media. With these corrections, the predicted pressure drops are very close to measured resistance values. A sample of the new results is presented here. It is especially encouraging that the insertion of "full-slip" criterion at the fiber boundaries reduces the predicted pressure drops to slightly less than the measured values, while the "zero-slip" results are slightly above the measured values.

Keywords: Air Filters, Boundary Layer, CFD-Simulation, Fibrous Filter, Filter Media, Filter Medium Resistance, Flow in Complex Structures, Knudsen and Molecular Diffusion, Navier-Stokes Equations, Pressure Drop

Introduction

Fibrous air filters have very complex geometries, as is apparent from any scanning electron microscope image of such media. A typical example is shown in Figure 1. The fibers (here of glass) are both curved and straight, have diameters of a range of values, and are joined to each other by a polymeric bonding material having completely random shapes. So long as studies were constrained by classic analytical mathematics, the description of the geometry of fibrous filter structures was necessarily greatly simplified, and subtle effects lost. The development of computational fluid dynamics (CFD) procedures allows far better simulations of gas flows through such fibrous media than were possible using analytical methods. There are limits to CFD simulations; to simulate the flow through a geometry like Figure 1 in three dimensions would require immense computational power.

The present paper provides a mid-level simulation, preserving several important parameters of the filter medium, namely its fractional solids, the distribution of fiber diameters, and their essentially random spacing. Along with earlier studies (Refs 1-7), we simulate the actual three-dimensional structure with a two-dimensional section perpendicular to the plane of the filter medium. Those studies were reasonably successful in predicting filter media air flow resistance and particle capture efficiency in spite of drastic simplification of media geometry, encouraging our hope for predicting the influence of random fiber diameters and random spacing.

Refs. (5) and (6) describe flow within fibrous media and also the capture of particles, and the effect of particle accumulation. Our effort here is limited to establishing the flow field and predicting resistance in fibrous media, which is the first step toward prediction of particle capture and loading characteristics. Our work extends the analysis to a more realistic geometry with random fiber diameters and random spacing between fibers, rather than depending on “effective” values for these factors.

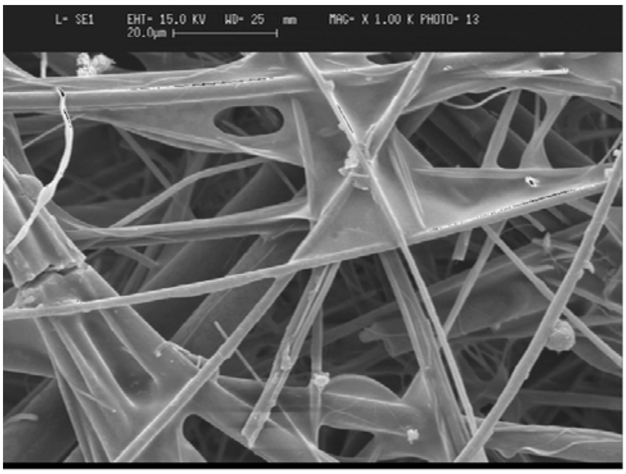


Figure 1 is a scanning electron microscope image of one glassfiber filter medium actually tested and simulated. The fibers are randomly oriented, have a range of diameters, and (being glassfibers) are approximately straight. The log-normal distribution of fiber length as a function of diameter characterizes this filter medium quite well. Measurements on the SEM photographs gave the log-normal distribution for all three media studied.

Figure 1 – SEM image of glassfiber filter medium

A full 3-dimensional simulation of the fibrous filter medium would of course match the real situation most accurately, but would also drastically increase computational demands.
A section through the filter medium perpendicular to the face of the medium would display an array of ellipses with randomly distributed minor and major axes. Ref. (7) presents photomicrographs showing this. An additional simplification, that the fiber bed can be simulated adequately by fibers parallel to each other and perpendicular to the general direction of air flow, changes the ellipses into circles. We decided to use this approach. Figure 2 shows an example of the 2-D section through a parallel-fiber medium, which is the computational domain used. The simplifying assumptions used are especially appropriate for the thin wet-laid filter media used in "mini-pleat" filters; for those media, fibers are long relative to their diameters, and are deposited in layers by papermaking processes.

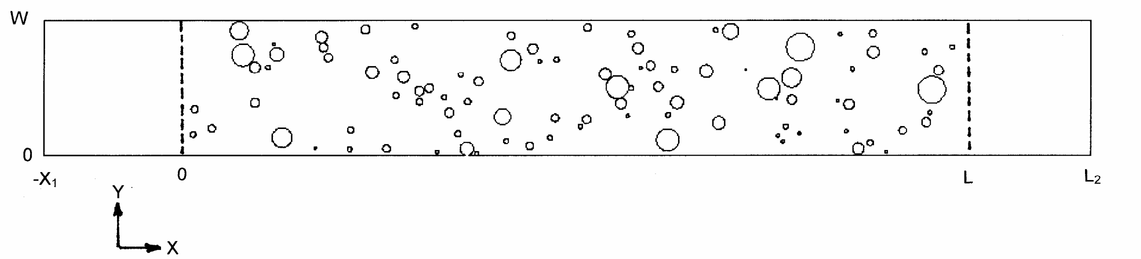


Figure 2 – Layout of simulated fibers generated randomly in computational domain

Layout of Circles for a CFD Domain Simulating Fibrous Media
For the computational domain shown in Figure 2, air flows from left to right in the direction of increasing x. To simulate the flow properly, we need to add fiber-free spaces upstream and downstream of the space occupied by fibers. These spaces are simulated by the area from $x = -X_1$ to $x = 0$ upstream of the fibers and from $x = L$ to $x = L_2$ downstream. The velocity is set uniform and parallel to the x axis at $x = -X_1$ (i.e. $v_x = V_o$ and $v_y = 0$). At $x = L_2$, the gradient of the pressure is set equal to zero. Boundaries at $y = 0$ and $y = W$ are assigned symmetry conditions; they are not impervious walls. The width ($y = 0$ to $y = W$) is made great enough to provide a representative slice of filter medium. In the actual sheet of filter medium, the y-dimension from 0 to W is much greater than the x-dimension from 0 to L.

Representation of the actual thickness of the filter media (L) was well within the computational abilities of the CFD code. Thicker media could be analyzed as far as resistance is concerned by using only a part of the thickness of the filter medium. However, analysis of particle capture and buildup demands that the full depth of media in the x-direction be provided; fewer and fewer particles remain available for capture as the flow penetrates deeper into the filter medium.

A short auxiliary computer program was written to locate the centers of the circles within the domain, and to assign diameters to each circle. The first section of the program generates a set of random numbers having a log-normal distribution with geometric mean diameter and geometric standard deviation the same as were measured for the fibers in the actual filter medium (see below). The second section of the program generates two random-number sets representing potential x- and y- coordinates of the circle centers. The uniform-random-number generator produced number sets between 0 and 1, so in each case the generated numbers must be multiplied by the appropriate scale factor (L for x-coordinate, W for y-coordinate). The program then goes down the list of coordinate pairs, matching each pair with the first unused diameter in the list of random diameters. In most cases, the first diameter is acceptable, but any of the following conditions will cause the diameter to be rejected:

1) If the diameter lies below the 2% probability or above a 98% probability for a complete log-normal distribution with the geometric mean and standard deviation used. (This truncation of the distribution is necessary because in fact the fibers have both a lower and upper diameter, while the complete log-normal distribution ranges from zero diameter to infinite diameter, both, of course, at zero probability).
2) If the circle of the selected diameter overlaps either of two boundaries [$y = \varepsilon$, $y = (W-\varepsilon)$ for $0<x<L$]. The value of ε is set to a small number, to allow air to flow around fibers close to the domain boundaries at $y = 0$ and $y = W$, thus allowing the domain to represent a slice cut from the center of a sheet of filter medium.
3) If the circle of the selected diameter overlaps any circle already selected.

If any of the three failure tests is met, the program steps down the list until an acceptable diameter is found. If no acceptable diameter is found, the coordinate pair is dropped from the coordinate list, and the next coordinate pair in the list examined. If the diameter is acceptable, it, and its coordinates, are stored in an output file for use by the CFD code.

During this selection process, the sum of the area of the circles is also calculated. When the ratio of this sum to the area (W·L) equals α, the fractional solids measured for the filter medium, the process is terminated.

Table 1 - Basic Parameters of Media Tested and Values Used for Simulation

	Units	Sample Data		
Sample		F6	F8	H13
Rated Velocity (v_r)	m/s	0.0617	0.0617	0.0231
Measured Geometric Mean Diam.(D_g)	μm	4.110	1.561	0.775
Generated Geometric Mean Dia. (D_g)	μm	4.101	1.545	0.756
Measured Geometric Std. Dev. (σ_g)	-	1.921	2.141	2.198
Generated Geometric Std. Dev. (σ_g)	-	1.871	2.070	2.195
Measured Fractional Solids (α)	-	0.076	0.081	0.092
Generated Fractional Solids (α)	-	0.078	0.081	0.092
Set Lower Diameter Limit, 2% Level	μm	1.00	0.35	0.15
Set Upper Diameter Limit, 98% Level	μm	15.5	7.33	3.76
Measured Pressure Drop (Δp)	Pa	11	42	121
Domain Depth (L)	μm	430	350	350
Domain Width (W)	μm	75	35	20
Number of Circles in Domain	-	94	200	480

Because there are occasional rejections of center coordinates, the geometric mean diameter d_g and geometric standard deviation σ_g of the selected set of circle diameters will not be exactly the same as d_g and σ_g measured for the fibers and used to generate the coordinate and diameter lists. Table 1 shows that the effect of rejected coordinates and diameters by the selection criteria is very small.

Measurement of Filter Media Properties

Sample Selection
Media samples were cut from rolls supplied by the manufacturer, using randomized locations down the length and width of the roll. Variances of measured parameters were found to be small, but random sample selection avoids any systematic parameter biases.

Fiber Diameter Distributions
More than 20 scanning-electron microscope (SEM) images were taken of each of the three media types. Approximately 1000X magnification allowed the least diameters to be seen and measured, while preserving enough area of the filter medium to allow representative sampling. Again, a randomization technique was used to eliminate bias and simultaneously weight the diameters by the length of each diameter interval present. Parallel lines were scratched across the SEM photographs at randomly-located positions. Wherever these lines intersected a fiber, the width of the fiber was measured in the direction normal to the fiber axis. A special scale was prepared to allow rapid sorting of the fiber diameters at each line/fiber intersection. Several hundred intersections (hence fiber diameters) were included from each media type.

These data were fitted to a log-normal distribution to obtain the two parameters d_g and σ_g.. The computer program for domain layout described above eliminated the tails of the fiber diameter distribution, dropping diameters with less than 2% and greater than 98% probability. These values appeared to match the diameter ranges missing from the SEM photographs.

Fractional Solids
The (volume) fractional solids in the media (α) is:

$$\alpha = \frac{M_m \left[\dfrac{\eta}{\rho_{fiber}} + \dfrac{1-\eta}{\rho_{binder}} \right]}{L} \qquad (1)$$

Fibers of glassfiber filter media have a melting point above the ignition temperature of organic binders. Baking at 500 °C burns the binder out of the media. Weighing media samples before and after baking thus allows the calculation of fiber mass fraction η. Values of 2450 kg/m^3 for fiber density ρ_{fiber} and 1000 kg/m^3 for binder density ρ_{binder} were thought reasonable.

Thickness and Compression

The thickness of the filter medium was measured, along with the compression function (the relation between the thickness of the medium and the pressure drop across it) using the technique described in Ref.(8). A stack of square, equal-area sheets of samples of the same medium is assembled. A rigid square sheet of aluminum of the same area is placed on top of the stack. Balance weights are added successively to the sheet, while measuring the height of the stack. The equivalent pressure (in Pa) on the medium is g·m/a, where g is the acceleration of gravity ($m \cdot s^{-2}$), m the mass of the plate plus any added balance weights (kg) and a is the area of the samples of medium in the stack (m^2). For these thin, wet-laid media sheets, the compression measured was negligible. A simple caliper measurement confirmed the stack measurements used to obtain *L*.

Resistance

The resistance-vs.-velocity characteristics of flat sheets of media were measured in a test duct which exposed an area of media 300 mm by 300 mm. Complete filter cells from these grades of filter media contain enough media area to reduce the average media velocity below 0.1 m/s and hence the expected resistance of a single sheet of medium to very low, difficult-to-measure levels. Accuracy of resistance measurement was improved by measuring the resistance of a 10-sheet stack. In the range of interest, resistance is essentially proportional to velocity.

CFD Considerations

Flow Regime

The applicable flow equations and boundary conditions depend on both the flow regime and the degree of "slip" at the fiber boundaries. Flow regimes are delimited by the Reynolds number of the flow around the fiber. There is no definable velocity of approach to randomly-disposed fibers. Table 2 gives the maximum Re values resulting from using the average velocity in the gaps between fibers, which is $v = v_r/(1\text{-}\alpha)$. The values of Re are such that everywhere in the calculation domain the flow is well within the laminar range.

Fiber Boundary Conditions: Slip

The molecules in a gas move about in random fashion, colliding with both solid surfaces and other molecules. These collisions create both pressure in the gas and viscous drag when the gas passes over any solid surface. The "mean free path" of the gas molecules, the average distance traveled by each molecule between collisions, is a function of the number of molecules per unit volume, which is a function of both temperature and pressure.

When the objects in the path of a gas flow are large relative to the gas mean free path, there are many simultaneous or nearly simultaneous collisions between gas molecules and surface, and the individual collisions are not apparent. Since there are so many collisions with each direction of impact equally probable, the gas at the body surface behaves as if the molecules there had zero tangential velocity, i.e. it is standing still. This is the condition of "continuum flow", and a force tangential to the surface, viscous drag, is generated. The condition is also called the "no slip" condition.

For quite small bodies in the flowing gas, far fewer collisions between gas molecules and the surface of the body occur in a given time interval. The gas at the surface no longer behaves as if it were standing still; the tangential velocity at the surface is non-zero, and various degrees of "slip" are said to occur- the flow has entered a new regime, "slip flow".

The criterion determining the shift from one regime to another for a body in a flow is the Knudsen number Kn, which is λ/D, [mean free path of air] divided by [object characteristic dimension]. In our case, the characteristic dimension is fiber diameter. Continuum flow is fully established at Kn = 0.001 ,and the Navier-Stokes (N-S) equations with no-slip boundary equations apply. For 0.001 < Kn <0.1, the N-S equations with "full slip" boundary conditions apply. For Kn > 10, "molecular flow" conditions apply, and the N-S equations no longer describe the behavior at all. The range 0.1 < Kn < 10 is a transition between slip and molecular flow, also requiring a set of flow equations different from the Navier-Stokes (Refs. 9 and 10).

Using the Standard Atmosphere value for λ, which is 0.06633 μm, for the F6 medium the range of Kn is from 0.004 to 0.06 (see Table 1). Thus "zero slip" conditions should apply at the F6 fiber boundaries. These conditions are, for incompressible flow with constant viscosity:

- the normal component of air velocity is zero;
- the tangential component of air velocity = (Kn/(1+Kn)) (normal component of the gradient of the tangential velocity).

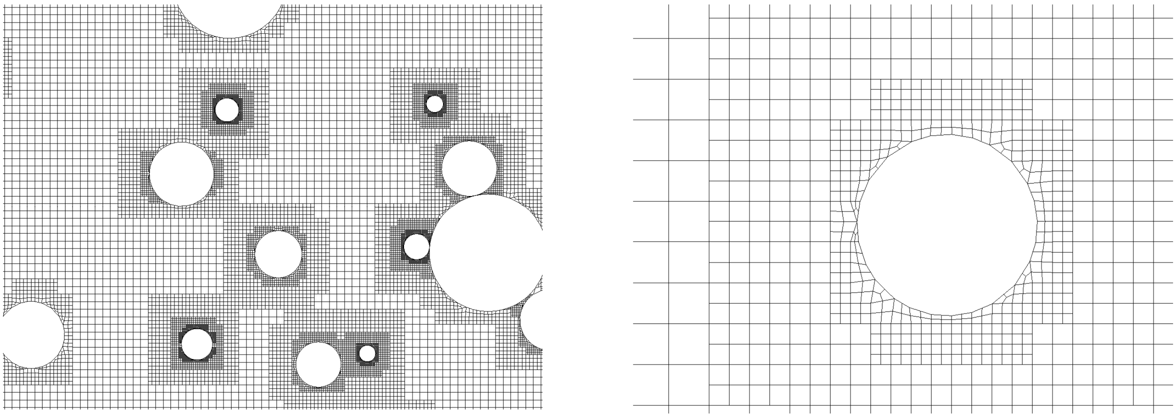
Table 2 – Slip-Related Parameters for Media Tested

	Units	Sample Data		
Sample		F6	F8	H13
Rated Velocity (v_r)	m/s	0.0617	0.0617	0.0231
Measured Fractional Solids (α)	-	0.076	0.081	0.092
Effective Velocity (v)	m/s	0.0668	0.0676	0.0258
Max. Reynolds Number (Re= $\rho D_{Max}/\ \mu$)	-	0.0690	0.0329	0.0063
Set Lower Diameter Limit , 2% Level	μm	1.00	0.35	0.15
Knudsen Number (Kn_L) at Lower Limit	-	0.06	0.18	0.42
Set Upper Diameter Limit, 98% Level	μm	15.5	7.33	3.76
Knudsen Number (Kn_U) at Upper Limit	-	0.004	0.009	0.017

Table 2 shows the values of Knudsen Number for the lower and upper fiber diameter limits for the three media types studied. For the F8 and H13 media, conditions range from "full slip" to "partial slip". We have not yet had the opportunity to incorporate all these conditions into the CFD code available, but runs using the N-S equations with zero slip and full slip boundary conditions predict resistances which closely bracket the measured values, indicating that more accurate predictions will be possible with fairly simple modifications to the code.

CFD Simulations

The CFD code first employed was the widely-used commercial code STAR-CD Version 3.2, provided by CD-Adapco. This is a finite-volume code with adaptive grid-generation ability, using double-precision floating point variables. Portions of the actual grid used in our first simulations are shown in Figures 3a and 3b. The figures show the distorted cells used to link the square cells in the bulk flow regions to the quasi-circular fiber boundaries. Note the change of cell dimensions to improve resolution in the regions near the circles (which simulate fiber boundaries). Initial runs were made for relatively low cell counts, which were then increased to check for grid scale independence. The plotted streamline fields (A portion of which is shown in Figure 4) looked very plausible.



(a) (b)

Figure 3 (a) Part of the early-run computational domain showing grid refinement near fibers.
(b) Same domain near a fiber showing polygons (distorted cells) at fiber boundary

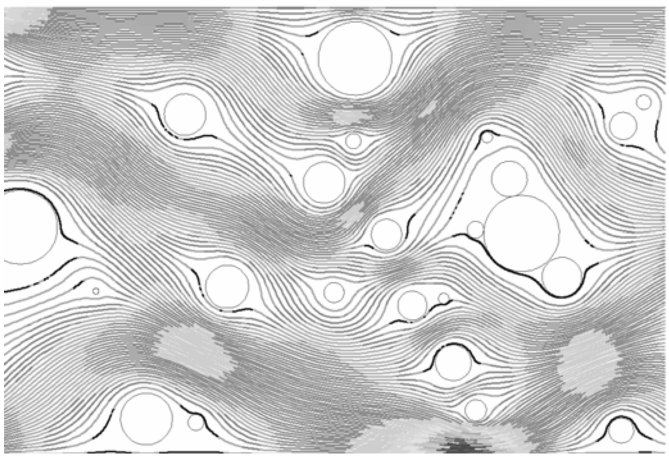


Figure 4 – Detail of CFD-simulated streamlines, early run

The grid-independence study, however, was disappointing. Table 3 shows the CFD-calculated resistances using cell counts from 34343 to 2300000. The prediction for resistance using slip conditions is, as it should be, lower than that predicted with zero slip. The prediction of resistance for the least cell count using slip conditions was reasonably close to the measured value for the medium simulated (13.3 Pa simulated vs. 11 Pa measured). However, there was no leveling-off of the calculated values when cell counts were increased; indeed, the indication is that calculated resistance would increase indefinitely with increasing cell counts

Table 3. Early Grid-Independence Study for Filter Medium F6 (Measured Resistance 11 Pa)

Number of Cells in Domain	34343	136232	544859	2300000	Fiber Boundary Condition
Air Flow Resistance, Pa	21.3	22.7	26.3	30.4	No Slip
Air Flow Resistance, Pa	13.3	14.3	16.3	18.2	Full Slip

To study this problem, a much simplified geometry was analyzed. The domain studied contained a single 10 μm diameter fiber. Even for this geometry, with body Re = 0.02 and Kn= 0.007, grid independence was not reached. The CFD simulation was repeated for a single 10000 μm diameter fiber, which made Re = 20, with considerably better results. (See Table 4). The code evidently had some problems in dealing with micro-scale elements and very low Reynolds numbers. Note that the comparison in Table 4 is expressed in fiber drag rather than resistance. However, fiber drag is proportional to resistance.

Table 4. Study of Grid Independence for Single Fibers

Number of Cells Around Fiber	80	160	320	Fiber Diameter, μm
Total Air Flow Drag, 10^{-6} N/m	21.3	22.7	26.3	10
Total Air Flow Drag, 10^{-6} N/m	13.3	14.3	16.3	10000

The problem has been studied and corrected by the CFD code vendor. We will report the rather extensive results of their corrected calculations in a later paper. The concept for simulating fibrous filter media geometry described here was used for these later studies, which do indeed yield excellent resistance predictions, and therefore offer the possibility for accurate particle capture calculations. We list in Table 5 a summary of the prediction of resistances for the three media studied as the number of cells in the domain was increased to 4 and 16 times the base number. The pressure drop (resistance) values are closer to the full-slip calculated values, as expected. A further code modification which allows partial-slip correction, based on fiber Reynolds Number, is planned.

Table 5. Grid-Independence Study for Filter Media F6, F8 and H13 (Air Flow Resistances, Pa, After Solver Modifications)					
Number of Cells in Domain	61000	245000	981000	Measured	Fiber Boundary Condition
Type of Filter Medium					
F6	18	18	18	11	No Slip
	9	11.9	12		Full Slip
F8	65	66	66	42	No Slip
	30	48	40		Full Slip
H13	177	180	180	121	No Slip
	109	110	110		Full Slip

For these later CFD simulations, in addition to corrections to the solver (STAR-CD Version 4), a more sophisticated grid pattern was used, as show in Figure 5. Figure 6 shows, for all three media, the pattern of the calculated (scalar) velocities and the pattern of calculated pressure drops across the media using the code enhancements and zero slip.

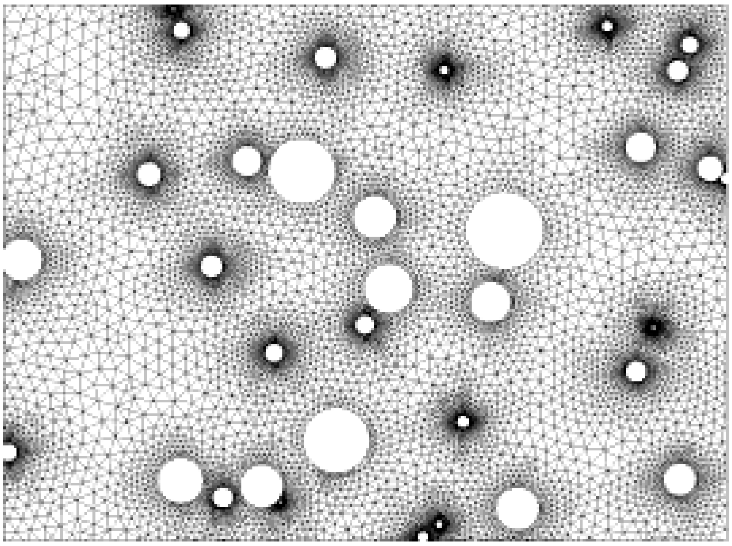


Figure 5 Portion of triangular adaptive grid used by corrected CFD code, F6 filter medium

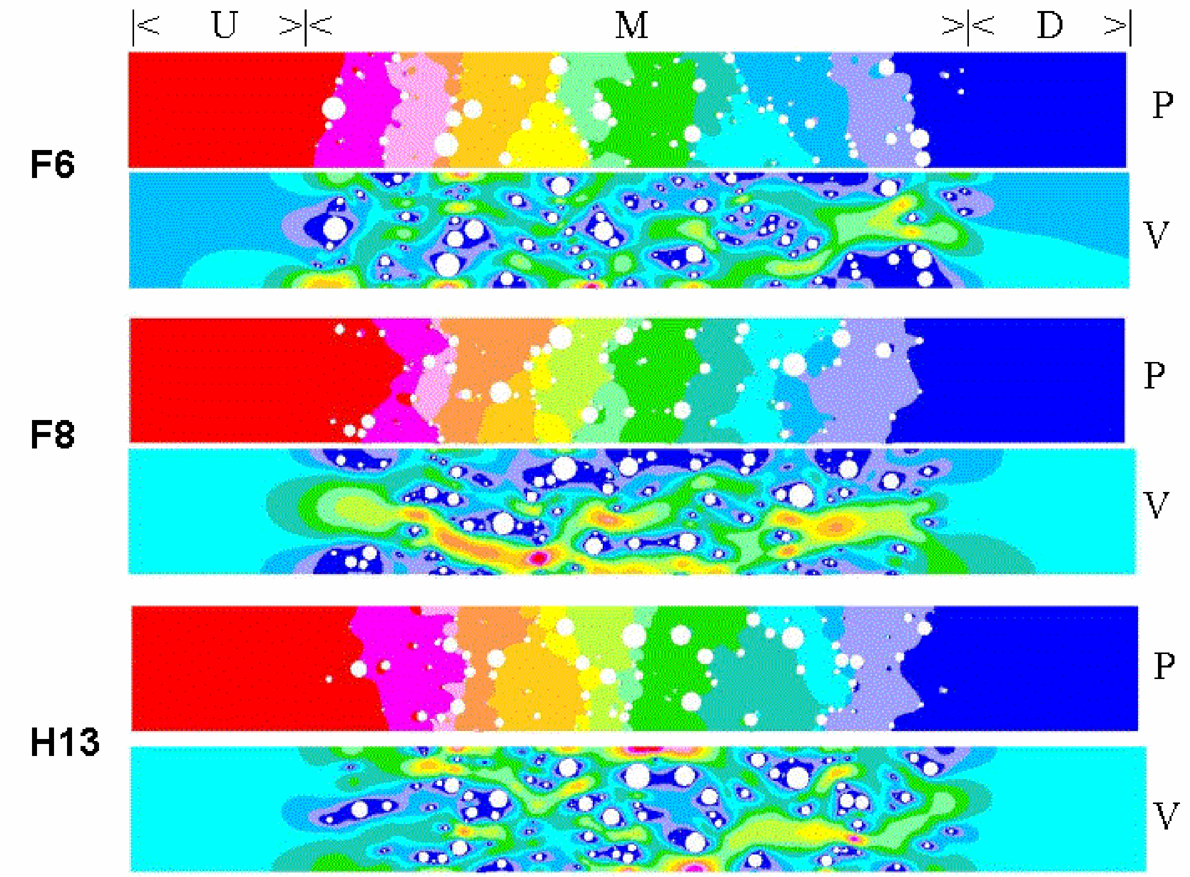


Figure 7. Calculated Patterns of Pressure and Scalar Velocities Across Filter Media F6, F8, and H13

Legend: U = region upstream of filter media, free of fibers
M = region occupied by filter media fibers
D = region downstream of filter media, free of fibers
P = pressure pattern; pressure drops from left to right
V = velocity pattern; flow from left to right

Conclusions

A procedure is presented for CFD simulation of filter media having log-normal fiber diameter distributions with realistic (random) fiber spacing. Although streamline patterns appeared correct, grid-scale independence was not achieved for this model with the fiber geometric mean diameter and flow velocity used. The vendor of the CFD code used has studied and corrected the problems in its code, and resistance predictions using this corrected code agree quite well with values for the three rather different media studied when full-slip boundary conditions are imposed. We suggest special caution in all CFD simulations of micrometer-scale geometries, and find grid-independence studies essential to reliable results. A growing body of literature on the uses of CFD in studies of micro-scale flow systems exists, (e.g. Refs. 9 and 10) provides guidance on this technology.

Nomenclature

L	thickness of the filter medium (= domain length), μm
M_m	mass of filter media per unit area, kg/m^2
p	pressure, Pa
v_r	rated velocity (air velocity at surface of medium), m/s
α	volume fraction of solids in the filter medium, -
μ	dynamic viscosity for air, Pa·s
η	mass fraction of solids in the filter medium, -
ρ	air density, kg/m^3
ρ_{fiber}	density of the (glass) fibers, kg/m^3
ρ_{binder}	density of the fiber binder in the medium, kg/m^3

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